5.2 ELECTROSTATIC PRECIPITATORS

This section discusses the basic operating principles, typical designs, industrial applications, and costs of electrostatic precipitators (ESPs). Collection of particles by electrostatic precipitation involves the ionization of the stream passing though the ESP, the charging, migration, and collection of particles on oppositely charged surfaces, and the removal of particles from the collection surfaces. In dry ESPs the particulate is removed by rappers which vibrate the collection surface. Wet ESPs use water to rinse the particles off.

Electrostatic precipitators have several advantages when compared with other control devices. They are very efficient collectors, even for small particles. Because the collection forces act only on the particles, ESPs can treat large volumes of gas with low pressure drops. They can collect dry materials, fumes, or mists. Electrostatic precipitators can also operate over a wide range of temperatures and generally have low operating costs. Possible disadvantages of ESPs include high capital costs, large space requirements, inflexibility with regard to operating conditions, and difficulty in controlling particles with high resistivity.[1]
Disadvantages of ESPs can be controlled with proper design.

5.2.1 Particle Collection

Particle collection during electrostatic precipitation is the end result of several steps. These steps include the establishment of an electric field, corona generation, gas stream ionization, particulate charging, and migration to the collection electrode. One typical ESP arrangement is shown in Figure 5.2-1.[2] In this illustration, the discharge electrode is a weighted wire and the collection electrode is a pipe. A wire-pipe ESP would contain many such wires and pipes.

5.2.1.1 Electric Field

The electric field plays an important role in the precipitation process in that it provides the basis for generation of corona required for charging and the necessary conditions for establishing a force to separate particulate from the gas streams.[2] An electric field is formed from application of high voltage to the ESP discharge electrodes; the strength of this electric field is a critical factor in ESP performance.[3]

The electric field develops in the interelectrode space of an ESP and serves a three-fold purpose. First, the high electric field in the vicinity of the discharge electrode causes the generation of the charging ions in an electrical corona; second, the field provides the driving force that moves these ions to impact with and attach their charge to the particles; and thirdly, it provides the force that drives the charged particulate to the collection electrode for removal from the effluent gas stream.[2]

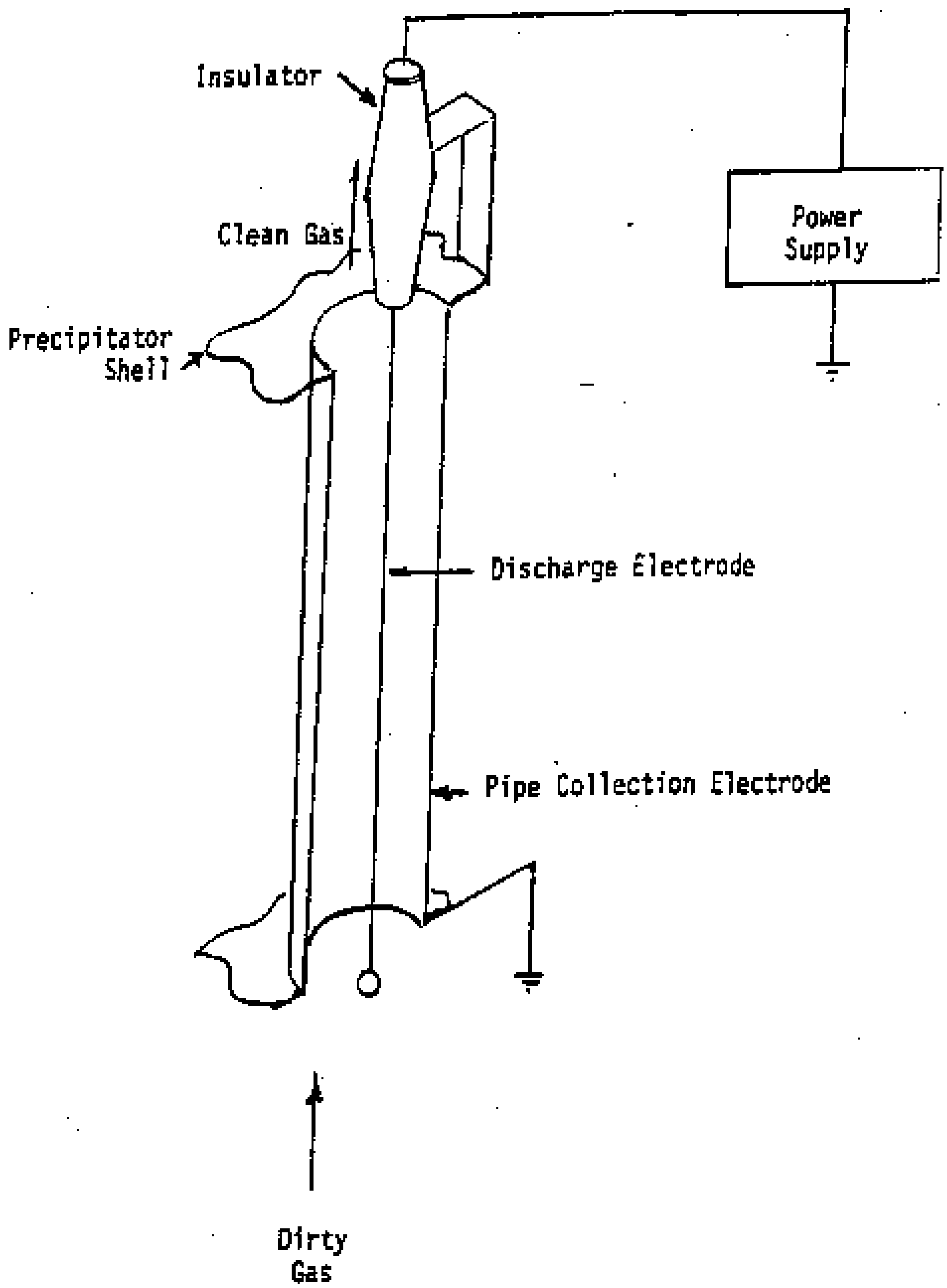


Figure 5.2-1. Cutaway view of Wire-Pipe Electrostatic Precipitator (Reference 2).

The electric field in an ESP is the result of three contributing factors: the electrostatic component resulting from the application of a voltage in a dual electrode system, the component resulting from the space charge from the ions and free electrons, and the component resulting from the charged particulate. Each of these factors may assume a dominant role in the determination of the field in a given set of circumstances. For example, the electric field in the vicinity of the first few feet of the inlet section of an ESP collecting particulate from a heavily particulate-laden gas stream may be dominated by the particle space charge; while the field in the outlet section of a highly efficient ESP is usually dominated by the ionic space charge.[2]

The strength or magnitude of the electric field is an indication of the effectiveness of an ESP.[3] Two factors are critical to the attainable magnitude of the electric field in an ESP. First, the mechanical alignment of the unit is important. If a misalignment occurs in a localized region that results in a close approach between the corona and collection electrodes, the sparking voltage for that entire electrical section will be limited. The second is the resistivity of the collected particulate, which can limit the operating current density and applied voltage that results in a reduced electric field.[2]

5.2.1.2 Corona Generation

The corona is the electrically active region of a gas stream, formed by the electric field, where electrons are stripped from neutral gas molecules leaving positive ions. The positive ions are driven in one direction and the free electrons in another. The necessary conditions for corona formation include the presence of an electric field with a magnitude sufficient to accelerate a free electron to an energy required to ionize a neutral gas molecule on impact, and a source of electrons to act as initiating electrons for the process.[2]

Details of electric field generation were discussed above. In terms of electron sources, there is always a supply of free electrons available from the ionization of gas molecules by either cosmic rays, natural radioactivity, photoionization, or the thermal energy of the gas.[2]
The corona is generated by a mechanism which is commonly referred to as electron avalanche. This mechanism occurs when the magnitude of the applied electric field is great enough to accelerate the free electrons. When free electrons attain sufficient velocity, they collide with and ionize neutral gas molecules. Ionization occurs when the force of the collision removes an electron from the gas molecule, resulting in a positively charged gas molecule and another free electron. These newly-freed electrons are also accelerated and cause additional ionization.[2]

The corona can be either positive or negative; but the negative corona is used in most industrial ESPs since it has inherently superior electrical characteristics that enhance collection efficiency under most operating conditions.[3]

5.2.1.3 Particle Charging

Particle charging in an ESP (and subsequent collection) takes place in the region between the boundary of the corona glow and the collection electrode, where gas particles are subject to the generation of negative ions from the (negative) corona process.[3]

Upon entering the ESP, the uncharged dust particles suspended in the effluent gas stream are exposed to a region of space filled with ions and, in the case of negative corona, perhaps some free electrons. As these electrical charges approach the electrically neutral dust particles, an induced dipole is established in the particulate matter by the separation of charge within the particles.[2] As a dipole, the particle itself remains neutral while positive and negative charges within the particle concentrate within separate areas. The positive charges within the particle are drawn to the area of the particle closest to the approaching negative ion. As a negative ion contacts the particulate matter, the induced positive charges will retain some electrical charge from the ion. This results in a net negative charge on the previously neutral particulate. The presence of an electrical charge is required in order for the electric field to exert a force on the particle and remove the particulate from the gas stream.[2]

Charging is generally done by both field and diffusion mechanisms. The dominant mechanism varies with particle size. In field charging, ions from the corona are driven onto the particles by the electric field. As the ions continue to impinge on the dust particles, the charge on it increases until the local field developed by the charge on the particle causes a distortion of the electric field lines so that they no longer intercept the particle and no further charging takes place. This is the dominant mechanism for particles larger than about 0.5 :m.[3]

Diffusion charging is associated with ion attachment resulting from random thermal motion; this is the dominant charging mechanism for particles below about 0.2 :m. As with field charging, diffusion charging is influenced by the magnitude of the electric field, since ion movement is governed by electrical as well as diffusional forces. Neglecting electrical forces, diffusion charging results when the thermal motion of molecules causes them to diffuse through the gas and contact the particles. The charging rate decreases as the particle acquires charge and repels additional gas ions, but charging continues to a certain extent.[3]

The particle size range of approximately 0.2 to 0.5 :m is a transitional region in which both charging mechanisms are present but neither dominates. Fractional efficiency test data for ESPs have shown reduced collection efficiency in this transitional size range, where diffusion and field charging overlap.[3]

5.2.1.4 Particle Collection

The final step in particle collection in an ESP involves the movement of the charged particles towards an oppositely-charged electrode that holds the particles in place until the electrode is cleaned.

Typically, the collection electrodes are parallel flat plates or pipes that are cylindrical, square, or hexagonal.[2]

The movement of particles toward the collection electrode is driven by the electric field. The motion of larger particles (greater than 10 to 20 µm) will more or less follow a trajectory determined by the average gas velocity and average particle electrical velocity.[2] The trajectory for smaller particles (<10 µm) will be less direct, since the inertial effects of the turbulent gas flow predominate over the electrical velocity induced by the relatively smaller electric charge. The overall movement of smaller particles, however, will be towards the collection electrode. The cumulative collection efficiency of an ESP is generally dependent upon the fractional collection efficiency of these smaller particles, especially between 0.2 to 2.0 µm in size.[2]

5.2.2 Penetration Mechanisms

There are several conditions which can reduce the effectiveness of ESPs and lead to penetration of particulate. These conditions include back corona, dust reentrainment, erosion, saltation, and gas sneakage.

5.2.2.1 Back Corona

Back corona or reverse ionization describes the conditions where an electrical breakdown occurs in an ESP. Normally in an ESP, a corona is formed at the discharge electrode, creating electrons and negative ions which are driven toward the (positive) collection electrode by the electric field. This situation is reversed if the corona is formed at the (positive) collection electrode. A corona at this electrode generates positive ions that are projected into the interelectrode space and driven toward the discharge electrode.[2]

As the positive ions flow into the interelectrode space in an ESP, they encounter negatively charged particulate and negative ions. The electric field from the charged particulate exceeds that of an ion at most distances. Therefore, the majority of the positive ions flow toward the negatively-charged dust particles, neutralizing their charge. This neutralization of charge causes a proportionate reduction in the electrical force acting to collect these particles.[2]

A second mechanism by which back corona may be disruptive to ESP collection is due to a neutralization of a portion of the space charge that contributes to the electric field adjacent to the collection electrode. The space charge component of the electric field near the collection zone may be as much as 50 percent of the total field. Neutralization of the space charge reduces the total collection force by the same fraction.[2]

5.2.2.2 Dust Reentrainment

Dust reentrainment associated with dry ESP collection may occur after the dust layer is rapped clear of the plates. The first opportunity for rapping reentrainment occurs when the dust layer begins to fall and break up while falling. Dust particles are swept back into the circulating gas stream. The second opportunity occurs as the dust falls into the hopper, impacts the collected dust, and puffs up to form a dust cloud. Portions of this dust cloud are picked up by the circulating gas stream. Some of the dust may be recollected.[2]

Direct erosion of the collected dust from the collection electrode can occur when gas velocities exceed 10 feet per second (fps). Most ESPs have gas velocities less than 8 fps, while newer installations have velocities less than 4 fps. Saltation is theorized to be a minor form of reentrainment which occurs as particles are collected. As a particle is captured and strikes the collection electrode, it may loosen other particles which are resuspended in the gas stream. Other causes of reentrainment in an ESP are electric sparking, air leakage through the hopper, and electrical reentrainment associated with low resistivity particles.[2]

5.2.2.3 Dust Sneakage

The construction of an ESP is such that nonelectrified regions exist in the top of the ESP where the electrical distribution, plate support, and rapper systems are located. Similarly, portions of the collection hopper and the bottom of the electrode system contain nonelectrified regions. Particle-laden gas streams flowing through these regions will not be subjected to the collection forces and tend to pass through the ESP uncollected. The amount of gas sneakage and bypassing through nonelectrified regions will place an upper limit on the collection efficiency of an ESP.[2]

5.2.3 Types of Electrostatic Precipitators

Electrostatic precipitators are generally divided into two broad groups, dry ESPs and wet ESPs. The distinction is based on what method is used to remove particulate from the collection electrodes. In both cases, particulate collection occurs in the same manner. In addition to wet and dry options, there are variations of internal ESP designs available. The two most common designs are wire-plate and wire-pipe collectors. Electrostatic precipitators are often designed with several compartments, to facilitate cleaning and maintenance.

5.2.3.1 Dry ESPs

Dry ESPs remove dust from the collection electrodes by vibrating the electrodes through the use of rappers. Common types of rappers are gravity impact hammers and electric vibrators. For a given ESP, the rapping intensity and frequency must be adjusted to optimize performance. Sonic energy is also used to assist dust removal in some dry ESPs. The main components of dry ESPs are an outside shell to house the unit, high voltage discharge electrodes, grounded collection electrodes, a high voltage source, a rapping system, and hoppers. Dry ESPs can be designed to operate in many different stream conditions, temperatures, and pressures. However, once an ESP is designed and installed, changes in operating conditions are likely to degrade performance.[1,2,3]

5.2.3.2 Wet ESPs

The basic components of a wet ESP are the same as those of a dry ESP with the exception that a wet ESP requires a water spray system rather than a system of rappers. Because the dust is removed from a wet ESP in the form of a slurry, hoppers are typically replaced with a drainage system. Wet ESPs have several advantages over dry ESPs. They can adsorb gases, cause some pollutants to condense, are easily integrated with scrubbers, and eliminate reentrainment of captured particles. Wet ESPs are not limited by the resistivity of particles since the humidity in a wet ESP lowers the resistivity of normally high resistivity particles.[2,4]

Previously, the use of wet ESPs was restricted to a few specialized applications. As higher efficiencies have currently become more desirable, wet ESP applications have been increasing. Wet ESPs are limited to operating at stream temperatures under approximately 170°F. In a wet ESP, collected particulate is washed from the collection electrodes with water or another suitable liquid. Some ESP applications require that liquid is sprayed continuously into the gas stream; in other cases, the liquid may be sprayed intermittently. Since the liquid spray saturates the gas stream in a wet ESP, it also provides gas cooling and conditioning. The liquid droplets in the gas stream are collected along with particles and provide another means of rinsing the collection electrodes. Some ESP designs establish a thin film of liquid which continuously rinses the collection electrodes.[2,3]

5.2.3.3 Wire-Plate ESPs

Wire-plate ESPs are by far the most common design of an ESP. In a wire-plate ESP, a series of wires are suspended from a frame at the top of the unit. The wires are usually weighted at the bottom to keep them straight. In some designs, a frame is also provided at the bottom of the wires to maintain their spacing. The wires, arranged in rows, act as discharge electrodes and are centered between large parallel plates, which act as collection electrodes. The flow areas between the plates of wire-plate ESPs are called ducts. Duct heights are typically 20 to 45 feet.[2] A typical wire-plate ESP is shown in Figure 5.2-2.[2]

Wire-plate ESPs can be designed for wet or dry cleaning. Most large wire-plate ESPs, which are constructed on-site, are dry. Wet wire-plate ESPs are more common among smaller units that are pre-assembled and packaged for delivery to the site.[4] In a wet wire-plate ESP, the wash system is located above the electrodes.[2]

5.2.3.4 Wire-Pipe ESPs

In a wire-pipe ESP, a wire that functions as the discharge electrode runs through the axis of a long pipe, which serves as the collection electrode. The weighted wires are suspended from a frame in the upper part of the ESP. The pipes can be cylindrical, square, or hexagonal. An example of a wire-pipe design is provided in Figure 5.2-3. Previously, only cylindrical pipes were used; square and hexagonal pipes have currently grown in popularity. The space between cylindrical tubes creates a great deal of wasted collection area. Square and hexagonal pipes can be packed closer together, so that the inside wall of one tube is the outside wall of another.[4] This situation is illustrated in Figure 5.2-4.

Wire-pipe collectors are very effective for low gas flow rates and for collecting mists. They can use dry or wet cleaning methods, but the vast majority are cleaned by a liquid wash. As with wire-plate collectors, the cleaning mechanism in a wire-pipe ESP is located above the electrodes. These pipes are generally 6 to 12 inches in diameter and 6 to 15 feet in length.[2]

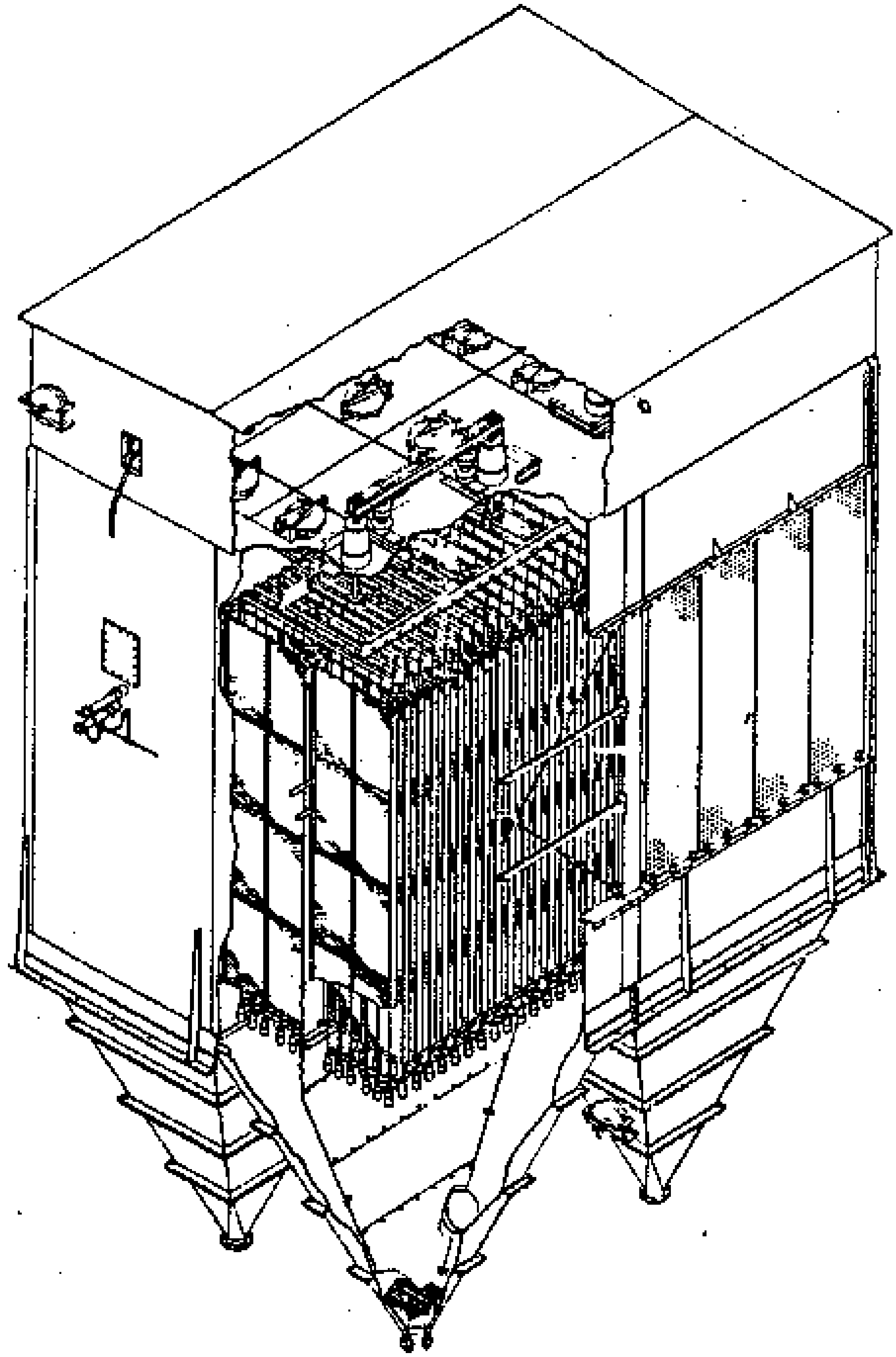


Figure 5.2-2. Wire-Plate Electrostatic Precipitator (Reference 2).

5.2-11

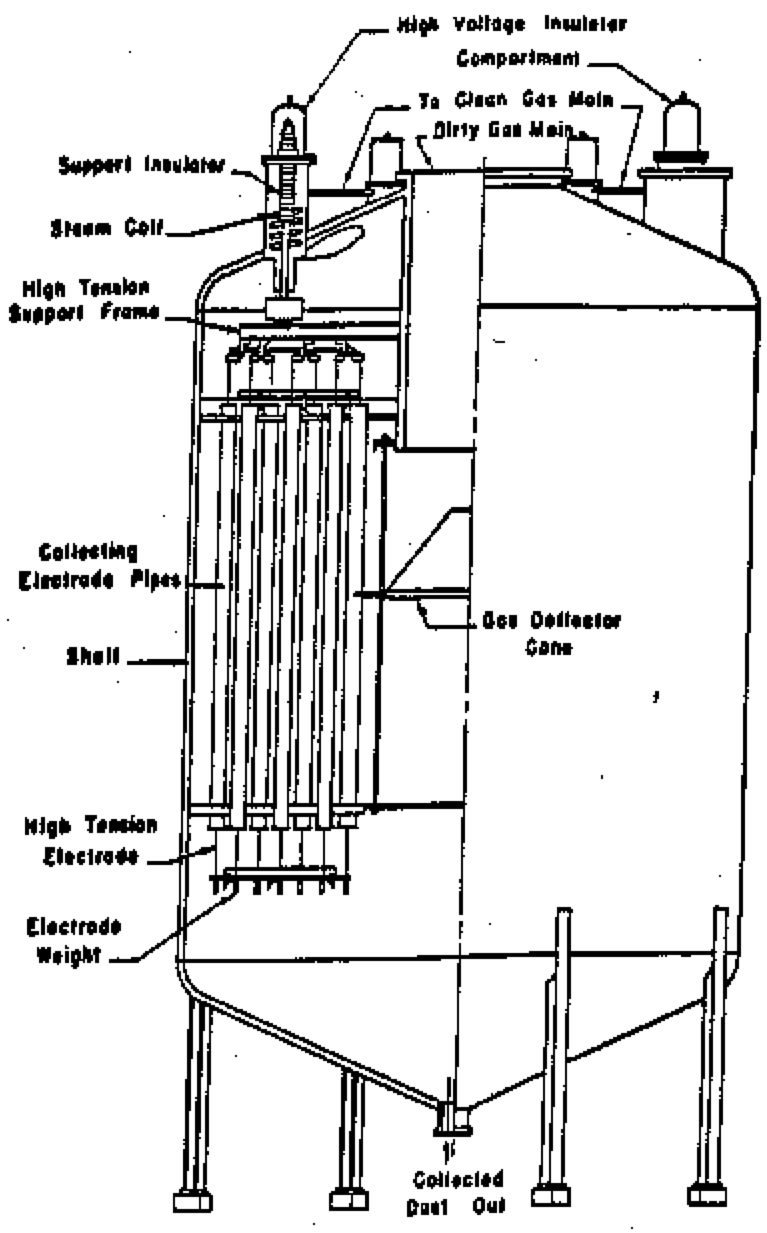


Figure 5.2-3. Wire-Pipe Electrostatic Precipitator (Reference 2).

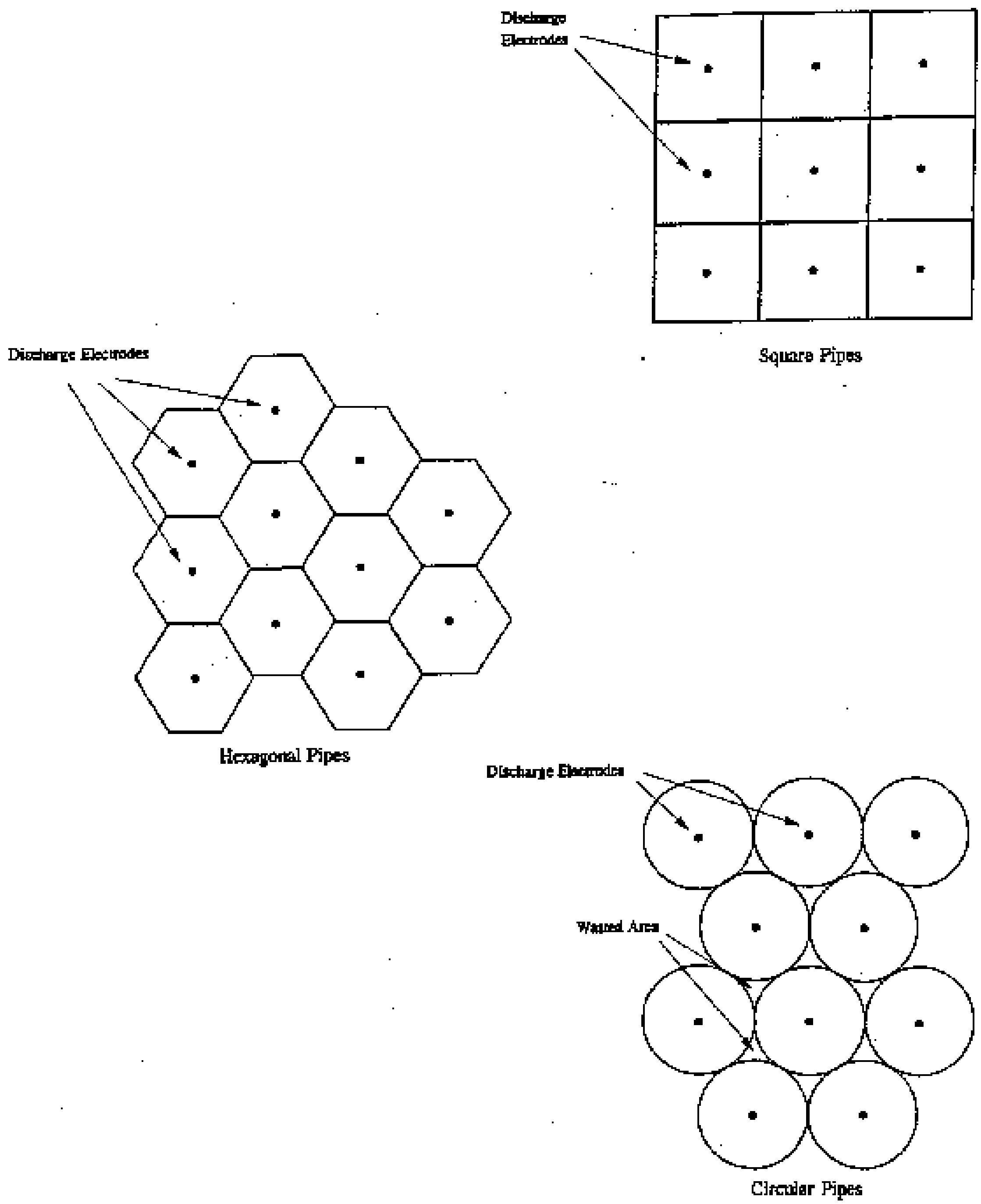


Figure 5.2-4. Square, Hexagonal, and Circular Pipe Arrangements for Wire-Pipe Precipitators (adapted from Reference 4).

5.2.3.5 Other ESP Designs

Rigid-Frame Plate. This ESP design is very similar to the wire-plate ESP, with the exception that the discharge electrode is a rigid frame, rather than a series of weighted wires, that is placed between plates. The frame supports wire discharge electrodes. This type of ESP operates in the same manner as the wire-plate and can be wet or dry. In general, the rigid frame design is more durable than weighted wires, but has higher initial (capital) expense.[2,3] Rigid frames have become the preferred design in some industries, such as pulp and paper.[5] Figure 5.2-5 provides an example of a rigid frame-plate ESP.

Wide-Plate Spacing.[6] The flow areas between the plates of a conventional wire-plate ESP usually vary from 8 to 12 inches in width. A recent enhancement in these units has been wide-plate spacings of up to 20 inches. Wide spacing gives a higher collecting field strength due to the resultant increase in space charge, a more uniform current density, and higher migration velocities. More variation in the discharge electrode geometry is also possible with wide-plate spacing. Because of the increased efficiency associated with this technique, less plate area is needed, thereby reducing the overall size and cost of the ESP.[7]

Electrode Variations.[1,2] In addition to the rigid frames, there are several other variations of electrodes that are not as common. In some cases, completely rigid discharge electrodes are preferred over weighted wires or rigid frames with wires.[1] Other discharge electrode designs are square wires, barbed wires, serrated strips of metal, and strips of metal with needles at regular intervals. The barbs, serration, and needles on the discharge electrodes help to establish a uniform electric field. In some cases, flat plates are used both as discharge and collection electrodes. Collection electrodes are often modified with baffles to improve gas flow and particle collection. Some ESPs use wire mesh rather than flat plates as collection electrodes. Examples of discharge electrodes and collection plates are shown in Figure 5.2-6.

Concentric Plate.[3] In this design, the ESP consists of vertical cylinders that are arranged concentrically and act as collection electrodes. The walls of the cylinders are continually rinsed by a thin film of liquid which is supplied by a system above the electrodes. The discharge electrodes are made of wire mesh located between the cylinders. This type of ESP is only operated as a wet ESP. The gas stream is wetted in a scrubber before it reaches the ESP. The concentric plate ESP is illustrated in Figure 5.2-7.

Pulsed Energization.[2] Some ESPs have experienced success with pulsed energization. Conventional ESPs rely on a constant base voltage applied to the discharge electrode to generate the corona and electric field. In pulse energization, high voltage pulses of short duration (of a few microseconds) are applied to the discharge electrodes. A typical pulse energization system will operate with pulse voltages on the order of 100 kilovolts (kV) rather than the 50 kV used with conventional energization. The pulses produce a more uniformly current distribution on the collection electrode.[8]

Pulses can be used alone or in addition to a base voltage and have been shown to increase the collection efficiency of ESPs with poor energization. Pulse energization has been used successfully in the electric utility industry. The Ion Physics Corp. has performed tests of this procedure at Madison Gas and Electric, Madison, Wisconsin.[9] This technique is,

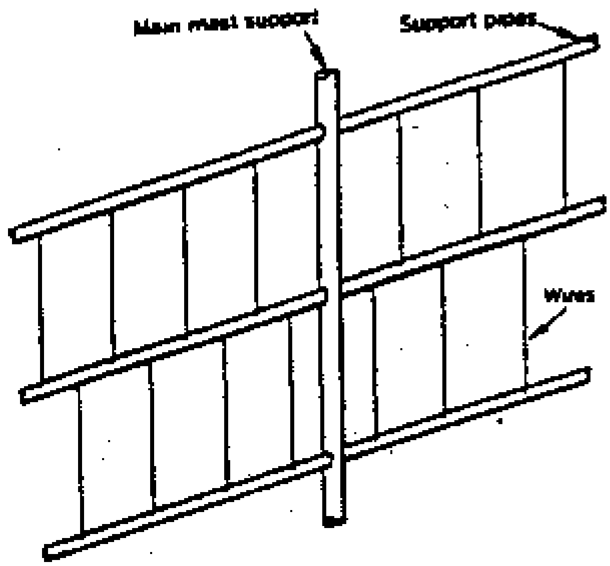


Figure 5.2-5. Rigid Frame Electrode (Reference 2).

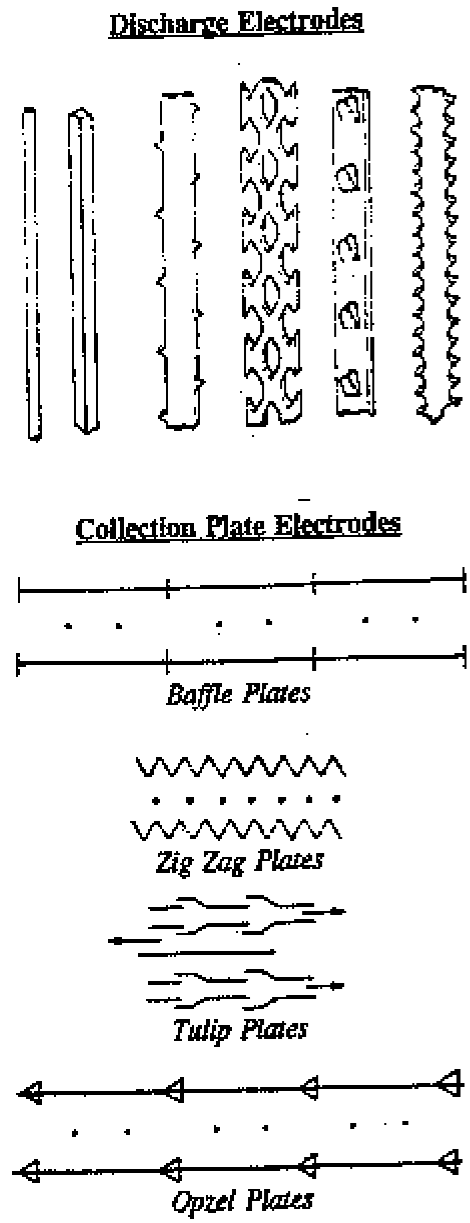


Figure 5.2-6. Various Discharge Electrodes and Collection Plate Designs (Reference 2).

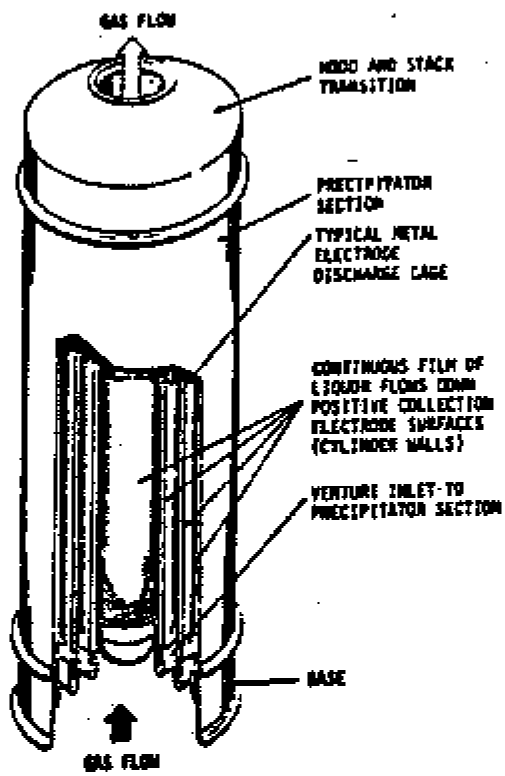


Figure 5.2-7. Concentric Plate Electrostatic Precipitator (Reference 3).

however, still evolving to permit a more rational approach to pulse energization and, perhaps, to reduce the cost.[6]

Two-Stage ESP.[2,3] All of the ESP designs mentioned previously have been single-stage ESPs. In a single stage ESP, particle charging and collection take place simultaneously in the same physical location. Two-stage ESPs are different in that particle charging takes place in a separate section which precedes collection. Two-stage ESPs are best suited for low dust loadings and fine particles. It is often used for cleaning air in buildings.

5.2.4 Collection Efficiency

Electrostatic precipitators are capable of collecting greater than 99 percent of all sizes of particulate.[1] Collection efficiency is effected by several factors including dust resistivity, gas temperature, chemical composition (of the dust and gas), and particle size distribution.

The resistivity of a dust is a measure of its resistance to electrical conduction and it has a great effect on the performance of dry ESPs. The efficiency of an ESP is limited by the strength of the electric field it can generate, which in turn is dependent upon the voltage applied to the discharge electrodes. The maximum voltage that can be applied is determined by the sparking voltage. At this voltage, a path between the discharge and collection electrodes is ionized and sparking occurs. Highly resistive dusts increase sparking, which forces the ESP to operate at a lower voltage. The effectiveness of an ESP decreases as a result of the reduced operating voltage.[2]

High resistivity dusts also hold their electrical charge for a relatively long period of time. This characteristic makes it difficult to remove the dust from the collection electrodes. In order to loosen the dust, rapping intensity must be increased. High intensity rapping can damage the ESP and cause severe reentrainment, leading to reduced collection efficiency. Low dust resistivities can also have a negative impact on ESP performance. Low resistivity dust quickly loses its charge once collected. When the collection electrodes are cleaned, even with light rapping, serious reentrainment can occur.[2]

Temperature and the chemical composition of the dust and gas stream are factors which can influence dust resistivity. Current is conducted through dust by two means, volume conduction and surface conduction. Volume conduction takes place through the material itself, and is dependent on the chemical composition of the dust. Surface conduction occurs through gases or liquids adsorbed by the particles, and is dependent on the chemical composition of the gas stream. Volume resistivity increases with increasing temperatures and is the dominant resistant force at temperatures above approximately 350°F. Surface resistivity decreases as temperature increases and predominates at temperatures below about 250°F. Between 250 and 350°F, volume and surface resistivity exert a combined effect, with total resistivity highest in this temperature range.[2,3]

For coal fly ash, surface resistance is greatly influenced by the sulfur content of the coal. Low sulfur coals have high resistivity, because there is decreased adsorption of conductive gases (such as SO_3) by the fly ash. The collection efficiency for high-resistance dusts can be improved with chemical flue gas conditioning that involves the addition of small amounts of chemicals into the gas stream (discussed in Section 5.1, Pretreatment). Typical chemicals include sulfur dioxide (SO_2), ammonia (NH_3), and sodium carbonate. These chemicals provide conductive gases which can substantially reduce the surface resistivity of the fly ash.[?,10] Resistivity can also be reduced by the injection of steam or water into the gas stream.[2]

In general, dry ESPs operate most efficiently with dust resistivities between 5×10^3 and 2×10^{10} ohm-cm.[2] Electrostatic precipitator design and operation is difficult for dust resistivities above 10^{11} ohm-cm.[2] Dust resistivity is generally not a factor for wet ESPs.[1,2] The particle size distribution impacts on the overall performance of an ESP. In general, the most difficult particles to collect are those with aerodynamic diameters between 0.1 and 1.0 :m. Particles between 0.2 and 0.4 :m usually show the most penetration. This is most likely a result of the transition region between field and diffusion charging. Figure 5.2-8 provides cumulative collection efficiency curves for ESPs operating in the utility, copper, and iron and steel industries. The curves were derived from emission factors.[11] Table 5.2-1 presents the cumulative collection efficiencies for PM_{10} and $PM_{2.5}$.

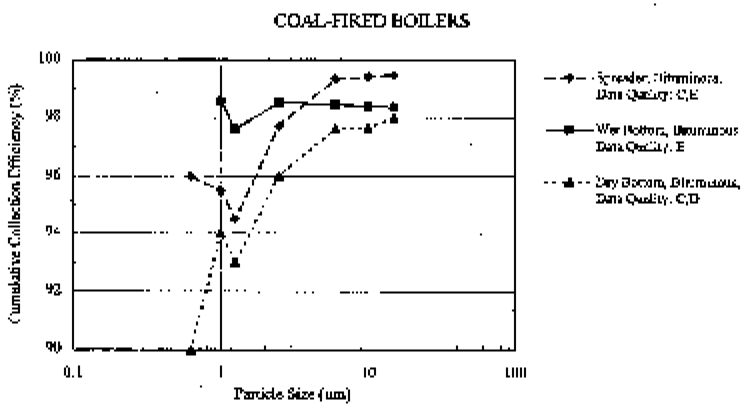
5.2.5 Applicability

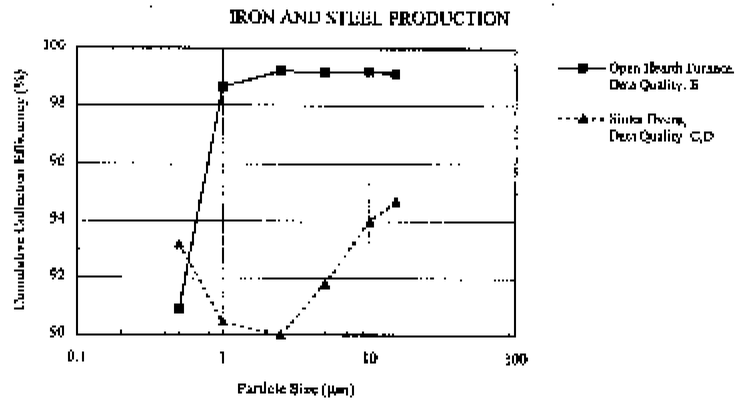
Approximately 80 percent of all ESPs in the U.S. are used in the electric utility industry. Many ESPs are also used in pulp and paper (7 percent), cement and other minerals (3 percent), iron and steel (3 percent), and nonferrous metals industries (1 percent).[1] Table 5.2-2 lists common applications of ESPs.[12]

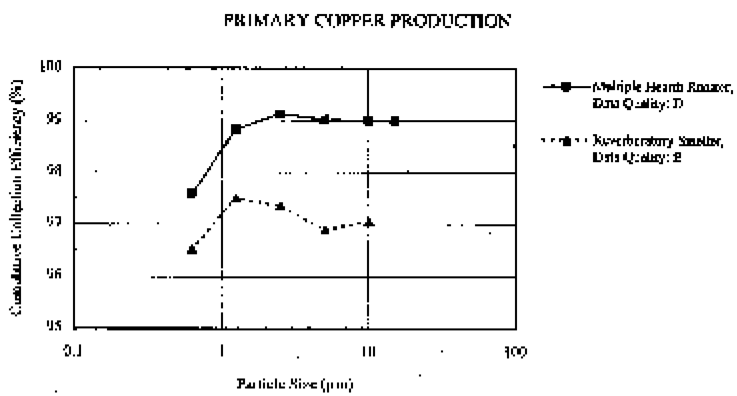
The dust characteristics can be a limiting factor in the applicability of dry ESPs to various industrial operations. Sticky or moist particles and mists can be easily collected, but often prove difficult to remove from the collection electrodes of dry ESPs. Dusts with very high resistivities are also not well suited for collection in dry ESPs. Dry ESPs are susceptible to explosion in applications where flammable or explosive dusts are found.[2]

Wet ESPs can collect sticky particles and mists, as well as highly resistive or explosive dusts. Wet ESPs are generally not limited by dust characteristics, but are limited by gas temperatures. Typically, the operating temperatures of wet ESPs cannot exceed 170°F. When collecting a valuable dust which can be sold or recycled into the process, wet ESPs also may not be desirable, since the dust is collected as a wet slurry that would likely need additional treatment.[2,4]

Electrostatic precipitators are usually not suited for use on processes which are highly variable, since frequent changes in operating conditions are likely to degrade ESP performance. Electrostatic precipitators are also difficult to install on sites which have limited space because ESPs must be relatively large to obtain the low gas velocities necessary for efficient particle collection.[1]







Note: Data quality refers to the data quality ratings assigned to the emission factors from which the efficiencies were calculated (from Reference 8).

A = excellent
B = above average
C = average
D = below average
E = poor

Figure 5.2-8. Cumulative Collection Efficiency Data for Electrostatic Precipitators at Coal-Fired Boilers, Primary Copper Producters, and Iron and Steel Production Operations (Reference 8).

Table 5.2-1. PM_{10} and $PM_{2.5}$ Cumulative Collection Efficiencies for ESPs at Coal Combustors, Primary Copper Operations, and Iron and Steel Production Operations (from Reference 11)

Application	Collection Efficiency (percent) PM_{10}	$PM_{2.5}$
Coal-Fired Boilers		
Dry bottom (bituminous)	97.7	96.0
Spreader stoker (bituminous)	99.4	97.7
Spreader stoker (anthracite)	98.4	98.5
Primary Copper Production		
Multiple hearth roaster	99.0	99.1
Reverberatory smelter	97.1	97.4
Iron and Steel Production		
Open hearth furnace	99.2	99.2
Sinter oven	94.0	90.0

Table 5.2-2. Typical Industrial Applications of Electrostatic Precipitators (from References 2 and 12)

Application	Source Category Code	Type of ESP[a]
Utility Boilers (Coal, Oil)	1-01-002...004	DESP, Wire-Plate
Industrial Boilers (Coal, Oil, Wood, Liq. Waste)	1-02-001...005 1-02-009, -013	DESP, Wire-Plate
Commercial/Institutional Boilers (Coal, Oil, Wood)	1-03-001...005 1-03-009	DESP, Wire-Plate

Application	Source Category Code	Type of ESP[a]
Chemical Manufacture	3-01-001...999	Site specific
Non-Ferrous Metals Processing (Primary and Secondary)		
Copper	3-03-005 3-04-002	DESP, WESP, Plate-Plate, Wire-Plate, Wire-Pipe, Rigid Frame-Plate
Lead	3-03-010 3-04-004	DESP, WESP, Plate-Plate, Wire-Plate, Wire-Pipe, Rigid Frame-Plate
Zinc	3-03-030 3-04-008	DESP, WESP, Plate-Plate, Wire-Plate, Wire-Pipe, Rigid Frame-Plate
Aluminum	3-03-000...002 3-04-001	DESP, WESP, Wire-Plate, Wire-Pipe Rigid Frame-Plate
Other	3-03-011...014 3-04-005...006 3-04-010...022	DESP, WESP, Wire-Plate, Wire-Pipe
Ferrous Metals Processing		
Coke Production	3-03-003...004	WESP, Wire-Pipe
Ferroalloy Production	3-03-006...007	DESP, Wire-Plate
Iron and Steel Production	3-03-008...009	DESP, WESP, Wire-Plate, Wire-Pipe
Gray Iron Foundries	3-04-003	DESP, Wire-Plate
Steel Foundries	3-04-007, -009	DESP, WESP, Wire-Plate, Wire-Pipe
Petroleum Refineries and Related Industries	3-06-001...999	DESP, Wire-Plate
Mineral Products		
Cement Manufacturing	3-05-006...007	DESP, Wire-Plate
Stone Quarrying and Processing	3-05-020	Site specific
Other	3-05-003...999	DESP, WESP, Wire-Plate, Needle-Plate
Wood, Pulp, and Paper	3-07-001	DESP, Wire-Plate, Rigid Frame-Plate
Incineration (Municipal Waste)	5-01-001	DESP, Wire-Plate, Rigid Frame-Plate

[a] DESP = Dry ESP, WESP = Wet ESP.

Table 5.2-2, continued

5.2.6 Costs of Electrostatic Precipitators

The costs of installing and operating an ESP include both capital and annual costs. Capital costs are all of the initial equipment-related costs of the ESP. Annual costs are the direct costs of operating and maintaining the ESP for one year, plus such indirect costs as overhead; capital recovery; and taxes, insurance, and administrative charges. Please refer to Chapter 6 of the *OAQPS Control Cost Manual* for cost equations.[13]

5.2.6.1 Capital Costs

The total capital investment (TCI) for ESPs includes all of the initial capital costs, both direct and indirect. Direct capital costs are the purchased equipment costs (PEC), and the costs of installation (foundations, electrical, piping, etc.). Indirect costs are related to the installation and include engineering, construction, contractors, start-up, testing, and contingencies. The direct and indirect installation costs are calculated as factors of the PEC.[13] Table 5.2-3 presents the TCI cost factors for ESPs. There are several aspects of ESPs which impact the PEC. These factors include inlet gas flow rate, collection efficiency, dust and gas characteristics, and various standard design features. The PEC is estimated based on the ESP specifications and is typically correlated with the collecting area in two ways, the Deutsch-Anderson equation or the sectional method.[13] Please refer to Chapter 6 of the OAQPS Cost Manual (Reference 13) for ESP cost estimation equations.

<u>Inlet Flow Rate</u>. The inlet flow rate has the greatest effect on TCI because it determines the overall size of the ESP. As the gas flow rate increases so does the ESP size and, in turn, the costs. Typical gas flow rates for ESPs are 10,000 to 1,000,000 actual cubic feet per minute (ACFM).[2] Electrostatic precipitator costs increase approximately linearly with gas flow rate, with the slope of the cost curves dependent on the other factors discussed below.

<u>Collection Efficiency</u>. Electrostatic precipitators are designed to achieve a specific collection efficiency. The TCI costs of ESPs increase as greater efficiencies are achieved. To attain higher collection efficiencies, ESPs must be larger to provide greater collection areas. In addition, extremely high efficiencies may require special control instrumentation and internal modifications to improve gas flow and rapping efficiency. Figure 5.2-9 shows the effect of collection efficiency on TCI costs for an ESP.[14]

<u>Dust Characteristics</u>. Particle size distribution, adhesiveness, and resistivity are dust characteristics that affect ESP costs. The size distribution of the dust influences the overall ESP collection efficiency. For example, particles in the range of 0.1 to 1.0 :m are the most difficult for an ESP to collect. If many of the particles are in this range, it will be more difficult to achieve a given

collection efficiency and a larger, more expensive ESP will be required. If the dust is very sticky, dry ESPs will need to be made of more durable (and costly) materials to withstand the intense rapping needed to remove the dust from the collection electrodes. For this reason, a wet ESP is often preferred for very sticky dusts, which drives costs higher. Dust resistivity influences costs, since highly resistive particles will require the added operating expense of flue gas conditioning or the use of wet ESPs.[13]

Table 5.2-3. Capital Cost Factors for Electrostatic Precipitators (from Reference 10)

Cost Item	Factor
Direct Costs	
Purchased equipment costs	
ESP + auxiliary equipment	As estimated (A)
Instrumentation	0.10 A
Sales taxes	0.03 A
Freight	0.05 A
Total Purchased Equipment Cost, (PEC)	B = 1.18 A
Direct installation costs	
Foundations and supports	0.04 B
Handling and erection	0.50 B
Electrical	0.08 B
Piping	0.01 B
Insulation for ductwork	0.02 B
Painting	0.02 B
Total direct installation cost	0.67 B
Site Preparation and Buildings	As required (Site)
Total Direct Cost, DC	1.67 B + Site
Indirect Costs (installation)	
Engineering	0.20 B
Construction and field expense	0.20 B
Contractor fees	0.10 B
Start-up	0.01 B
Performance test	0.01 B
Model study	0.02 B
Contingencies	0.03 B
Total Indirect Cost (IC)	0.57 B
Total Capital Investment = DC + IC	2.24 B + Site

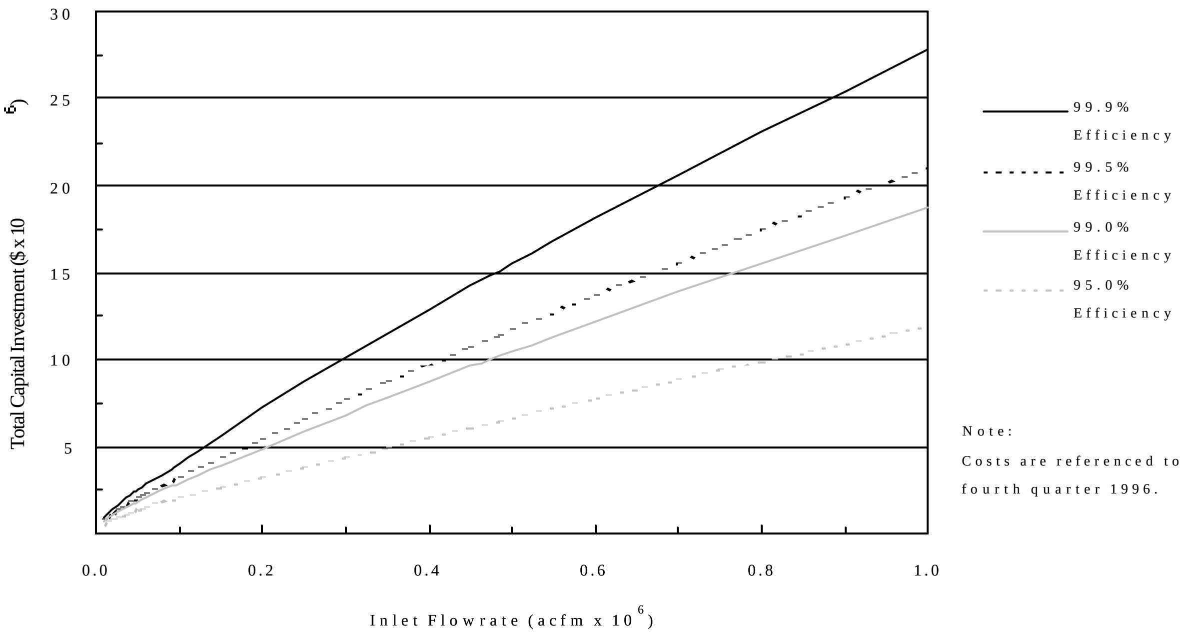


Figure 5.2-9. Effect of Design Collection Efficiency on ESP TCI Costs (Reference 14).

Gas Stream Characteristics. Important gas stream characteristics are temperature, moisture, and chemical composition. Gas stream temperature affects particle resistivity and, consequently, ESP efficiency and costs. Very moist streams and mists generally require the use of wet ESPs. The chemical composition of the gas stream may restrict the construction materials appropriate for the ESP. Most ESPs are constructed of carbon steel; however when the stream is highly corrosive, more costly corrosion resistant materials such as stainless steel, carpenter, monel, nickel, and titanium are needed.[13] Figure 5.2-10 shows the impact of the use of corrosion resistant materials on ESP TCI costs.[14]

Design Features. There are several design features that are considered standard for most ESPs and which can add up to 50 percent of the PEC. These options include inlet and outlet nozzles, diffuser plates, hopper auxiliaries (heaters, level detectors, etc.), weather enclosures, stair access, structural supports, and insulation.[13] Figure 5.2-11 shows ESP costs with and without these standard design features.[14] Wet ESPs and rigid-frame designs typically have higher initial (capital) expenses than dry and wire-plate ESPs.

5.2.6.2 Annual Costs

The total annual cost of an ESP consists of both direct and indirect costs. Direct annual costs are those associated with the operation and maintenance of the ESP. These include labor (operating, supervisory, coordinating, and maintenance), maintenance materials, operating

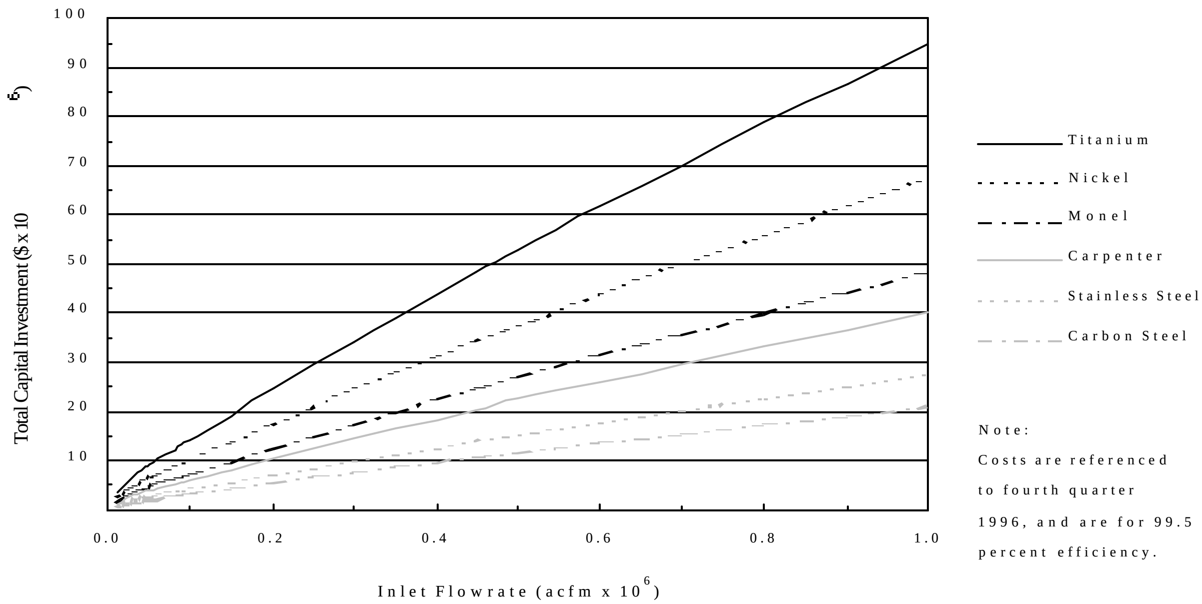


Figure 5.2-10. Effect of the Use of Corrosion Resistant Materials on ESP TCI Costs (Reference 14)

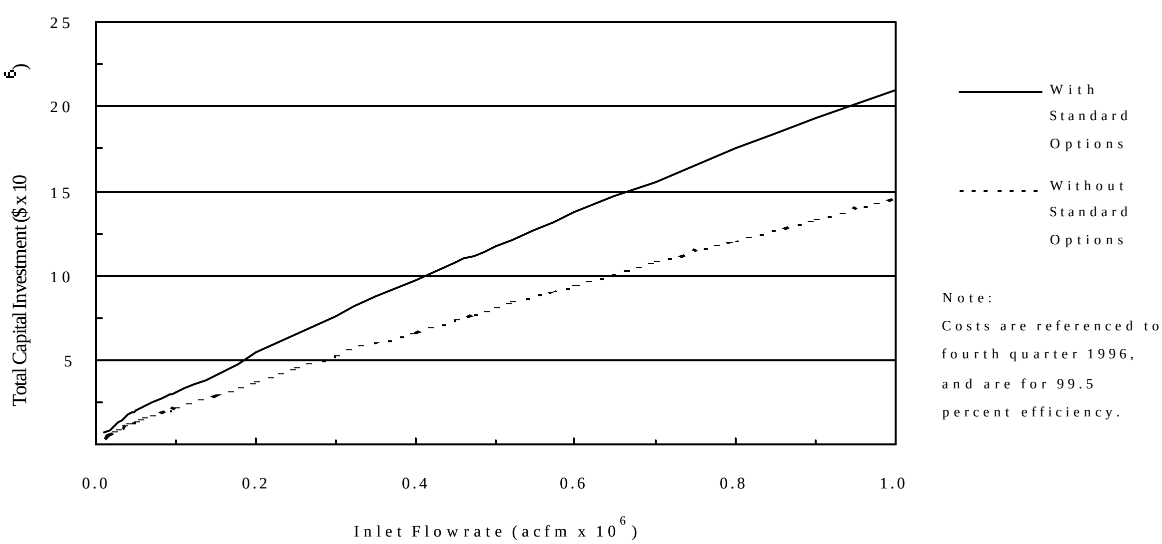


Figure 5.2-11. TCI Costs for ESPs With and Without Various Standard Design Features (Reference 14).

materials, electricity, dust disposal, wastewater treatment (wet ESPs), compressed air (for rappers), conditioning agents, and heating or cooling costs.[13] Some operating costs are not applicable to all ESPs. For ESPs collecting dusts which have no value, dust disposal can be expensive. Gas conditioning agents are used for ESPs that need to collect highly resistive dusts. Some ESP installations also require heating or cooling of the gas stream for effective operation. The cost of the heating fuel can be significant; cooling water costs generally are not.[13]

Indirect annual costs include taxes, insurance, administrative costs, overhead, and capital recovery. All of these costs except overhead are dependent on the TCI. Table 5.2-4 lists the annual cost parameters that impact ESP costs, with typical values provided for each parameter. Table 5.2-5 provides the annual cost factors for ESPs. It is difficult to generalize these costs for all ESPs, since annual costs are very site-specific.[13]

5.2.7 Energy and Other Secondary Environmental Impacts

The environmental impacts of ESP operation include those associated with energy demand, solid waste generation in the form of the collected dust, and water pollution for wet ESPs. The energy requirements for operation of an ESP consist mainly of electricity demand for fan operation, and electric field generation, and cleaning. Fan power is dependent on the pressure drop across the ESP, the flow rate, and the operating time. Assuming a fan-motor efficiency of 65 percent and a ratio of the gas specific gravity to that of air equal to 1.0, the fan power requirement can be estimated from the following equation:[13]

$$\text{Fan Power (kW-hr/yr)} = 1.81 \times 10^{-4}\,(V)(\Delta P)(t) \qquad \text{(Eq. 5.2-1)}$$

where V is gas flow rate (ACFM), ΔP is pressure drop (inches H_2O), t is annual operating time (hr/yr), and 1.81×10^{-4} is a unit conversion factor.

The operating power requirements for the electrodes and the energy for the rapper systems can be estimated from the following relationship:[13]

$$\text{Operating Power (kW-hr/yr)} = 1.94 \times 10^{-3}\,(A)(t) \qquad \text{(Eq. 5.2-2)}$$

where A is ESP plate area (ft^2), t is annual operating time (in hr/yr), and 1.94×10^{-3} is a unit conversion factor.

Wet ESPs have the additional energy requirement of pumping the rinse liquid into the ESP. Pump power requirements can be calculated as follows:[13]

$$\text{Pump Power (kW-hr/yr)} = (0.746(Q_l)(Z)(S_g)(t)) \,/\, (3{,}960\ \eta) \qquad \text{(Eq. 5.2-3)}$$

where Q_l is the liquid flow rate (gal/min), Z is the fluid head (ft), S_g is the specific gravity of the liquid, t is the annual operating time (hr/yr), O is the pump-motor efficiency, and 0.746 and 3,960 are unit conversion factors.

Table 5.2-4. Annual Cost Parameters for Electrostatic Precipitators (Reference 14).

Parameter	Description	Typical Values
Direct Cost Parameters		
Operating factor (OF)	Hours of scrubber operation per year	8,640 hr/yr
Operator labor rate (OR)	Operator labor pay rate	$12.50/hr[a]
Operator shift factor (OS)	Fraction of operator shift on scrubber	0.25[b]
Supervisor labor factor (SF)	Fraction of operator labor cost	0.15[b]
Coordinator labor factor (CF)	Fraction of operator labor cost	0.33[b]
Maintenance labor (ML)	Dependent on plate collector area	Site specific
Maintenance materials factor (MF)	Fraction of Purchased Equipment Cost	0.01[b]
Electricity rate (ER)	Cost of electricity	$0.07/kW-hr[a]
Chemicals (C)	Cost of chemical conditioning agents	Site specific (sect. 5.1)
Compressed air (CA)	Cost of compressed air for rappers	$0.18/1000 scf[a]
Wastewater treatment (W)	Cost of treating wet ESP effluent	$1.55-$2.55/1000 gal[a]
Waste disposal (D)	Cost of disposing of dust/sludge	$20-30/ton[a]
Indirect Cost Parameters		
Overhead factor (OV)	Fraction of total labor and (MM) costs	0.60[b]
Annual interest rate (I)	Opportunity cost of the capital	7 percent[b]
Operating life (n)	Expected operating life of scrubber	20 years[b]
Capital recovery factor (CRF)	Function of (n) and (I)	0.0944[c]
Taxes (TAX)	Fraction of the TCI[d]	0.01[b]
Insurance (INS)	Fraction of the TCI[d]	0.01[b]
Administrative costs (AC)	Fraction of the TCI[d]	0.02[b]

[a] Estimated for 1996 from currently available information.

[b] Estimates from "CO$T-AIR" Control Cost Spreadsheets (Reference 14).

[c] Capital Recovery Factor is calculated from the following formula: $CRF = \{I(1 + I)^n\} \div \{(1 + I)^n - 1\}$, where I = interest rate (fraction) and n = operating life (years).

[d] The total capital investment (TCI) can be escalated to current values by using the Vatavuk Air Pollution Control Cost Indicies (VAPCCI), described in Appendix B.

Table 5.2-5. Annual Cost Factors for Electrostatic Precipitators (Reference 14).

Cost Item	Formula[a]	Factor
Direct Costs		
Labor		
Operator (OL)	(OF)×(OR)×(OS)	A
Supervisor (SL)	(SF)×(OL)	0.15 A
Coordinator (CL)	(CF)×(OL)	0.33 A
Maintenance (ML)	Site specific	ML
Maintenance materials (MM)	(MF)×(PEC)	0.01 PEC
Electricity (E)	Power[b] × (ER)	E
Chemicals (C)	Site specific	C
Compressed air (CA)	(CA)	CA
Wastewater treatment (W)	(W)	W
Waste disposal (D)	(D)	D
Total Direct Cost (DC)		1.48 A + ML + 0.01 PEC + E + C + CA + W + D
Indirect Costs		
Overhead	(OV)×(OL+SL+CL +ML+MM)	0.89 A + 0.6 ML + 0.006 PEC
Capital Recovery	(CRF)×(TCI)	0.1424 TCI
Taxes	(TAX)×(TCI)	0.01 TCI
Insurance	(INS)×(TCI)	0.01 TCI
Administrative Costs	(AC)×(TCI)	0.02 TCI
Total Indirect Cost (IC)		0.89 A +0.6 ML + 0.006 PEC + 0.1824 TCI
Total Annual Cost (DC + IC)		2.37 A + 1.6 ML + 0.016 PEC + 0.1824 TCI + E + C + CA + W + D

[a] Includes values also described in Table 5.2-4.

[b] Equal to total power requirements, e.g. fan, pump, etc.

Solid waste is generated from ESP operation in the form of the collected dust. Although the dust is usually inert and nontoxic, dust disposal is a major factor of ESP operation. With some ESP operations, the dust can be reused in the process or on the facility or sold. Otherwise, the dust must be shipped offsite. Water pollution is a concern for wet ESPs. Some installations may require water treatment facilities and other modifications to handle the slurry discharge from wet ESPs.[2,13]

5.2.8 References for Section 5.2

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